1. a) Two identical $p$-type Si wafers ($N_a = 10^{17}$ cm$^{-3}$) have a phosphorus pre-deposition of $Q_0$ applied by ion implantation. A junction is created at a depth of 0.4 µm by heating the first wafer for 40 min at 1000°C. You want the junction depth at 0.2 microns. How long a time would you heat treat your second wafer if you used the same temperature? [5]

Ans: Using the diffusion length, $x = 2(Dt)^{1/2}$, you would have to cut the time to $\frac{1}{4}$th, or 10 min in order to reduce the diffusion length by a factor of 2.

b) Sketch on the figure at right the carrier concentration vs depth from part a) and label all the curves. [10]
Ans: Curves, labels at right in red.

2. Describe in one or two sentences the molecular-scale process that accounts for pressure (e.g. in a vacuum chamber) mentioning the properties of the molecules that determine the pressure. [5]

Ans: Pressure is due to the number of molecular collisions per unit area on a surface times the momentum of each molecule.
Chemical vapor deposition [25]

3. 
   a) Briefly describe the processes implied by each term in the equation for the velocity of CVD film growth: 
   \[ v_f = \frac{C_g}{N_f} \frac{1}{h_g + \frac{1}{k_s}} \] [10]

   b) Which of the processes in this equation are thermally activated? [5]

   c) Label on the CVD growth-vs.-1/T figure below the transport-limited regime and the reaction-rate limited regime. [5]

   d) From what part of this figure would you calculate the activation energy for this reaction? [5]

![Graph showing CVD growth-vs.-1/T with labels: Transport-limited, Reaction-rate limited, Log(v) vs. 1/T, Slope = -\Delta G.]

Ans:

   a) \( C_g \) is the concentration in the carrier gas of the species to be deposited; it sets an upper limit on the transport process. \( N_f \) is the number of molecules per unit area in the film. \( h_g \) is the gas transport coefficient governing the flow rate of gas across the boundary layer above the substrates. \( k_s \) is the reaction rate coefficient at the film surface.

   b) The reaction-rate constant is thermally activated, \( k_s = k_0 \exp[-\Delta G/kT] \).

   c) See red in figure above.

   d) The activation energy is given by the slope in the reaction-limited regime.
Oxidation [25]

4. Using what you know about the Deal-Grove model of Si oxidation, 
   \[ v_{\text{oxide}} = \frac{HP_s}{N_f} \left( 1 - \frac{x_{\text{oxide}}}{D} - \frac{1}{k_s} \right) \]
   label the figures below as either diffusion limited or reaction-rate limited and briefly explain why. [10]

   ![Graph](image)

   b) Given the growth-rate equation \( x_0^2 + Ax_0 = B(t + \tau) \), write the equation for the oxide thickness, \( x_{\text{ox}} \), as a function of time for thin and thick oxide layers. [5]
   
   c) Does Si oxidation occur faster or slower in the presence of water vapor? [5]
   
   d) Which method of Si oxide growth, wet or dry, is better suited for the gate oxide? [5]

Ans:

   a) **Diffusion or transport limited** because slope in oxide is not zero, all oxygen reaching interface reacts quickly
   
   ![Graph](image)

   **Reaction rate limited** because flat slope in oxide means there is a backup at reaction interface

   ![Graph](image)

   b) Thin oxide: \( x_{\text{ox}} = \frac{(B/A)(t + \tau)}{\alpha} \)
   Thick oxide: \( x_{\text{ox}} = \left[ B(t + \tau) \right]^{1/2} \)

   c) Oxidation is faster in H₂O.

   d) Dry-grown SiO₂ is of higher quality, therefore better for gate oxide.
Ion implantation, diffusion [25]

5. a) Sketch the form of the implanted concentration vs. depth for a typical ion implant. [5]

b) Overlay on your solution to part a) a dashed line to show what happens to the distribution upon annealing after the implant is complete. [5]

c) Consider the three mechanisms for implanted ions to give up their energy to a target: i) electronic viscosity, ii) local electronic excitations of target atoms, and iii) nuclear collisions. Which of these mechanisms is most responsible for the lateral broadening (perpendicular to the direction of implant) of the implanted profile? [5]

d) Describe the difference in the range of implant and the damage done to the target (assume Si) for boron and arsenic ions implanted at the same voltage and dose? [10]

Ans:

a,b) c) The third mechanism, momentum transfer by nuclear collisions, is most effective in changing the direction of the incident ions.

d) Boron implantation has a much greater range than arsenic (for similar voltage and dose) because its smaller mass is less effective in transferring energy to the target nuclei. In terms of damage, the same amount of kinetic energy is given up by each implant. Because boron is lighter, its kinetic energy is expressed in a greater velocity and hence a greater fraction of its energy is given up to electron viscosity, so overall B produces less damage than As.
Sputter deposition [25]

6. You are sputter depositing Al over an SiO$_2$ layer on a Si wafer.
   a) Which condition, $P_{ar} = 15$ mTorr or $P_{ar} = 5$ mTorr (all other parameters equal),
      would give a denser Al film (and therefore better electrical conductivity)? [5]
   b) Which substrate bias voltage would more likely give better step coverage, -100 V
      or -40 V (all else equal)? [5]
   c) You want to deposit a SiN layer. Would you use RF or DC sputter deposition? [5]
   d) You want to increase your sputter deposition rate for a silver (Ag, 108 amu)
      electrical contact. You had been using Ar (40 amu) sputtering gas. Which of the
      following changes would help increase Ag deposition rate: [10]
      i) Switch sputtering gas to Kr (83 amu).
      ii) Switch sputtering gas to Ne (20 amu).
      iii) Increase the anode-cathode potential difference.
      iv) Reduce the pressure in the chamber.

Ans:
   a) Lower pressure means fewer collisions for the Ag atoms drifting toward the
      substrate. They therefore arrive with greater kinetic energy and are able to diffuse
      to lower-energy sites, making a denser, higher-quality film.
   b) Better step coverage is achieved with a broader angular distribution of incoming
      Ag target atoms approaching the substrate. This occurs when the incoming
      species have lower energy, hence lower bias voltage is better.
   c) SiN is not a conductor so you cannot use DC sputtering. Use RF.
   d) i), iii) and iv) increase Ag deposition rate.
      i) Switching to Kr (better mass match to Ag) will increase the sputtering yield of
      Ag at the target. iii) Increasing the anode-cathode potential difference will
      increase the rate of sputtering from the target and increase the deposition rate.
      iv) Reduced pressure in the chamber increases the deposition rate because there
      are fewer collisions for Ag between the target and substrate.
Lithography and etching

7. a) For which type of lithography systems do Fraunhofer and Fresnel diffraction theory apply? Sketch the intensity profiles on a wafer for both types of lithography systems. [5]

**Ans:**

Fraunhofer = Projection  
Fresnel = Contact/Proximity

Source: Campbell p.157  
Source: Campbell p.156

b) Explain (using a sketch) how the Rayleigh criteria for resolution limit in a projection system is determined. [5]

**Ans:**

Determined as the distance between features when the peak of one projection lands on the first zero of the other.

c) In a projection lithography system, does an increase in spatial coherence of the source cause an increase or decrease in resolution if the CMTF of the resist is constant. Explain. [5]

**Ans:**

Could increase or decrease depending upon the CMTF of the resist.

d) Why does the addition of O\textsubscript{2} change etch rate in a CF\textsubscript{4}-based plasma etch. [5]

**Ans:**

Oxygen is added to CF\textsubscript{4} plasma to increase the amount of reactive F species (O reacts with CF\textsubscript{3} and CF\textsubscript{2} and hence reduces the recombination rate of F.).

e) The CH\textsubscript{3}COOH:HF:HNO\textsubscript{3} system is commonly employed to wet etch silicon. Explain the steps of this chemical etch process, i.e. explain the function of each chemical in the process. [5]

**Ans:**

HNO\textsubscript{3} acts as an oxidant to the silicon, HF etches the oxidized silicon. CH\textsubscript{3}COOH is used to dilute the solution.